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Hybrid Approach to Predict the Track Deterioration in a Railway in-Service: A Conceptual Design

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Abstract. The track supports the loads of the railway vehicles and guides their movements. Its excellence determines the permissible wheel load, speed, safety and reliability of the rail operation. None railway can expect to survive in a competitive economy if its track is an obstacle to safety, reliability and proper service. The effects of all adverse features on the track are cumulative and track components require a routine of attention and renewal at frequent intervals. If the permanent way is not perfectly levelled and aligned, irregularities cause oscillations or vibrations of the train, which can cause discomfort to the passenger and damage to the freight, and the worst: a catastrophic accident. In planning a new track or improving one in-service, it is important to be able to predict the probable asset deterioration rate as a function of the variables related to the train and its periodicity. This may contribute significantly in planning, engineering, operational, and maintenance activities. The aim of this paper is to present a conceptual design of a hybrid numerical and experimental approach to predict the track deterioration in a railway in-service based on empirical-mechanistic and probabilistic theories.

1. Introduction

The effects of all adverse traits on the permanent way are cumulative, and railway materials as rail, sleepers, fastenings and ballast require a routine of attention and renewal at frequent intervals [1]. If the permanent way is not perfectly levelled and aligned, irregularities cause oscillations or vibrations of the train, which can cause discomfort to the passenger and damage to the freight [2], and the worst: a catastrophic accident. Track condition has a significant influence on the railway system behaviour in terms of ride safety, maintenance and passenger comfort. However, in practice, it is physically impossible to totally eliminate track irregularities. Therefore, it is very important to understand the mechanism that underpins track deterioration to be able to predict the development of track irregularities, reduce railway system life-cycle cost, and design new track structures [3].

Track condition must be assessed by measurable deterioration parameters [4]. It is defined by the condition of its components and its geometry. These two groups of elements are closely interrelated within the complex process of track deterioration; if one is in poor condition this will contribute to deteriorate the other, and if the components are in poor condition it will not be possible to correct the



geometry efficiently [5]. Each parameter should be carefully weighed for its importance in influencing track performance.

During an extend literature survey, more than 100 methods (or studies) related to track deterioration were found, included other literature reviews. Very few of these models deal with several mechanisms as previously commented. This paper aims to build upon with relevant reviews a conceptual design of a hybrid numerical and experimental approach to predict the track deterioration in a railway in-service based on empirical-mechanistic and probabilistic theories, which may fill the current gaps.

Therefore, this paper is structured as follows. Section 2 presents a background of track components, track geometry, and forces and displacements acting on the track. Following this, in Section 3, it presents the current theoretical models and approaches regarding to track condition. In Section 3 is also shared the results related to the proposed Conceptual Design to deal with the complex process of the track deterioration. Finally, Section 4 concludes the paper and outlines the challenges to apply the new approach.

2. Background

The main function of the railway track is to support the loads of railway vehicles [1] and to guide their movements [6]. The permanent way must guide the vehicles without risk of derailment taking up vertical and horizontal forces – offing-load these forces via track grid and ballast bed into the subsoil, and ensure high passenger conform and high availability for train traffic [7]. To investigate the effect of a specific load on the track, the evaluation of the different functions is necessary.

In this paper, track conditions are divided conceptually in 2 groups of measurable parameters. The first one is the component deterioration parameter which is a general term to describe collectively the deterioration of each individual component in railway track. In other words, it is what, how, when, and how much the component with a specific composition, form, dimension, and mechanical properties loses its function into the permanent way. Thus, according to Guler [5], it is difficult to use a single descriptor to capture all deterioration modes.

On the other hand, there is a second group of measurable parameters namely the geometry degradation which is, according to Vale and Ribeiro [8], a random by nature. The track geometry is the position of the railway track in 3 dimensional spaces [9]. It is usual to characterize the geometry degradation by the evolution over time (or tonnage) of several geometrical parameters such as the longitudinal level, the alignment, the gauge, the twist and the cross level [8]. Figure 1 illustrates a typical ballasted track components and primary geometry parameters.

A modern conventional track can be subdivided into 7 components (rails, pads, sleepers, ballast, sub ballast, geosynthetics, and subgrade), each having a specific function in the train load support [10]. It is a fundamental part of railway infrastructure and its components can be classified into two main categories: superstructure and substructure. Both the superstructure and the substructure are mutually important to ensure the safety and comfort of passengers and quality of travel [11] and also the preservation of freight. There is no definite structural coordination in the permanent way. Rails, track joints, sleepers, ballast and subgrade experience differential movements among all components, with consequences on wear and deterioration. The lateral stability and the resistance to arch depend on the fit of the ballasted sleepers, the weight of the rail and the axle load [2], and speed. Rail support varies in stiffness, and local deformations in the roadbed cause (and are caused by) impacts due to loads applied dynamically at a wide variety of intensities. According to De Man [12], the development of the track structure – not to complicate – has some component properties more important than others. Mechanical properties and track design define the relationship between the forces acting on the track, and the forces, stresses and displacements occurring in and below the line.

The primary geometries parameters are measured in the track cross-section as drawn in figure 1. Each rail has 2 degrees of freedom (DoFs). These 4 DoFs are normally replaced by an equivalent system consisting of cant, level, alignment, gauge, and twist [13], which represent the track geometry. Li et al. [14] explain that the goal of measuring track geometry is to quantify deviations from the ideal design

with the aim of correcting this error as it approaches an established limit to maintain safety conditions and ride comfort. Descriptions, function, standards, and thresholds regarding each one of track components and track geometry elements are explained in [1], [15], [16], [13], [7], [2], and [14].

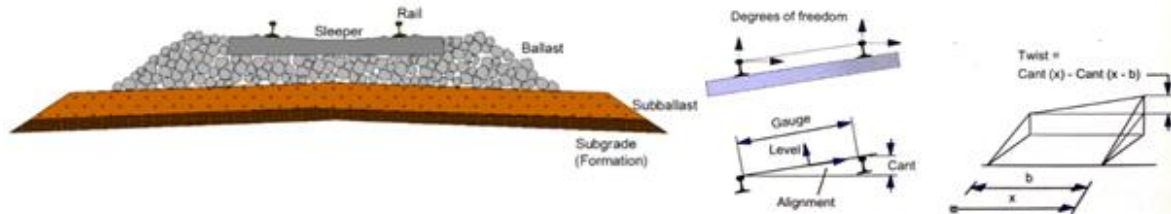


Figure 1. Typical ballasted track structure (left) [2] and primary geometry parameters [13]

According to Iwnicki [6], the principal difference between a railway vehicle and other types of wheeled transport is the guidance provided by the track. The rail surface not only supports the wheels, but also guides them in a lateral direction. The combination of rail vehicle and track should be regarded as one system. This applies to the function as a transport system, and also with respect to the technical point of view. A strong integration exists between the permanent way and the vehicles. The separation between both subsystems and the place where the interaction manifests itself is the contact between wheel and rail throughout the bearing and guidance of the vehicles [13].

Both the vehicle and the track have irregularities. The requirements for bearing strength and track depend to a large extent on the load parameters: axle load – static vertical load per axle, tonnage borne – sum of the axle loads, and running speed. The first one, to which the dynamic increment is added, in principle determines the track required strength. The second (tonnage borne) is a measure of when maintenance and renewal are necessary. The dynamic load component, which depends on speed and horizontal and vertical track geometry, also plays an essential part here [13]. According to Tzanakakis [2], deterioration or degradation is the reduction of the original quality due to various influences. By far the most significant factor contributing to the deterioration is the dynamic load. It is directly related to the axle load and track geometry. The main processes of track deterioration are: wear, fatigue, and settlement [2]. Many factors can affect track condition and suitable modelling techniques must be employed.

3. Conceptual Design Approach

The novels for track deterioration modelling may be classified into mechanistic and/or statistical models, and numerical and/or experimental approaches. “And/or” means that is possible to develop a combined models and approaches such as statistical and mechanistic model (empiric-mechanistic) or even a numerical and experimental approach (hybrid). Figure 2 shows a diagram, which represents, in theory, the modelling(s).

According to Bing and Gross [17], a basic methodology in degradation analysis is the statistical model which involves the analysis of a large sample observations of actual track performance and the affecting parameters. Correlation, variance and regression analyses may be used to develop track degradation models. However, variations in data recording and interpretation may invalidate the models. In turn, simulating the track degradation in this cyclic manner, it is possible to incorporate the compounding effect of uncertainties in predictions of the track deterioration processes. Figure 3 illustrates these uncertainties.

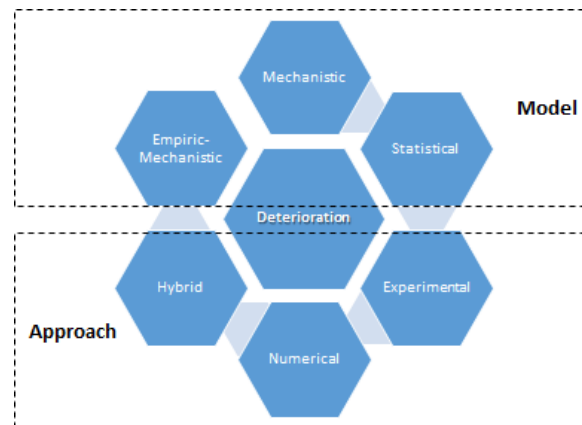


Figure 2. Diagram representing the track deterioration theoretical models and approaches

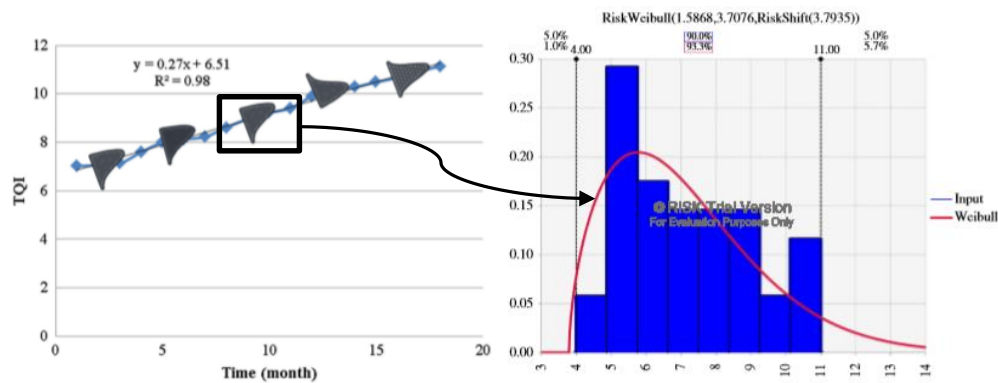


Figure 3. The track-quality index (TQI) data for the entire sections in a specific period of time with a Weibull distribution function fitted to the data (left) and track geometrical degradation model [18]

Over the past decade, significant improvements have been made in technologies and systems for track geometry measurements. Jovanovic et al. [19] present a set of condition monitoring methods that are used for railway infrastructure maintenance and renewal management around the world. According to Soleimanmeigouni et al. [20], there is an emerging trend for researchers regarding the use of statistical methods to model the track geometry degradation.

A statistical model uses a large amount of data about the output variable (track performance) and the descriptive or input variables (influence factors) to build a relationship between them [21]. An important class of statistical methods for modelling degradation is stochastic process, including the Wiener process, the Gamma process and the Inverse Gaussian process. The main advantage of this model is that since the actual data are used to build the degradation modelling, an accurate estimate track degradation is derived [21]. A major drawback is the lack of a mechanistic basis for track components and their interactions with influencing factors, and this may result in some unrealistic outcomes [22].

In turn, as an alternative, there is the mechanistic model, which involves establishing, by theory or by testing, the track component mechanical properties [23]. Mechanistic or physical models are based on a priori physical information. It consists in establishing the mechanical properties of all [24]. The advantage of this method is that the track response to traffic parameters can be incorporated, although the response of some track components is hard to quantify. For instance, a single defective fastening may not cause any noticeable effects, but several adjacent defective fastenings will affect the deterioration of other components, and the track as a whole.

The track structure analysis models based on the mechanical properties are successful in calculating forces, tensions and probability of failure developments in the individual permanent way components. An advantage for the solution may be incorporated, in addition to a response of some components from

the difficulty quantification [23]. In fact, these models cannot handle ranges of operating, environmental and maintenance conditions that demonstrate a different degradation behaviour [25]. Another major problem of the mechanistic model is to quantify the track and vehicle properties. Understanding the interactions between the components and track properties can also be difficult in some cases [25]. Other studies on the formulation of mechanistic models – and their advantages and disadvantages – are presented by Dahlberg [26] and Guler [5]. Figure 4 shows a typical track structure input parameters required by a mechanical model (D-Track), and an example of comparison in moving point analysis provided by the model.

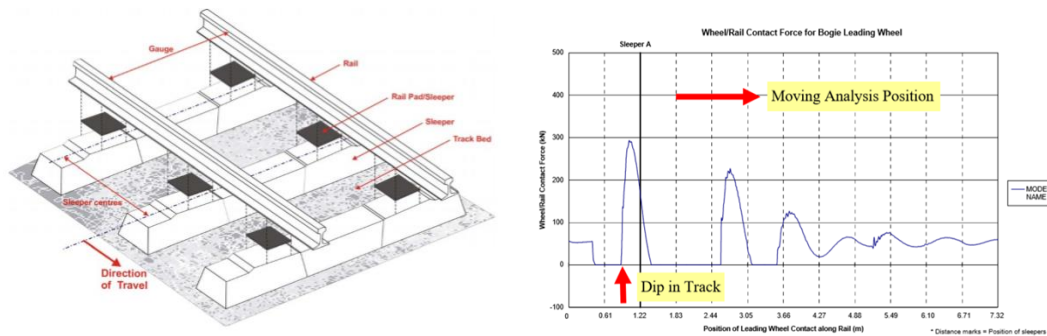


Figure 4. Track structure input parameters required (left) and an example in moving point analysis (forces along rail on wheel-rail contact) both in a mechanical model [27]

According to Soleimanmeigouni et al. [20], several researchers have been attempted to combine mechanistic and statistical models to use the best of both methodologies. Rhayma et al. [28] proposed a stochastic model adaptable to several mechanistic models to represent the track degradation behaviour and to deal with the inherent variability of its mechanical and geometric parameters. Sadeghi and Askarinejad [22] also developed a degradation model combining mechanistic novel and regression-based statistics that considered track geometry and structural condition data. The basic advantage derived from the use of an empirical-mechanistic model is that it allows the parameterization of geometry and basic properties. Therefore, these parameters can be altered and adapted to the different range requirements, taking into account spatial variations, temporal effects and fatigues of the elements.

Additionally, for the success of an empirical-mechanistic model, it is necessary to carry out laboratory and field experiments (track components), and measurement data (track geometry). The specimens in field must take into account the sort of segment (straight, curve, switch, bridge, tunnel, ramp up/down, etc.) and at laboratory need to build all the permanent way components (superstructure and substructure). It is substantial to avoid bias, and to practice error measurements and validation tests.

In turn, uncertainty is an important feature of the track geometry behaviour, and a mechanistic (or even a simple empirical-mechanistic) model is unable to capture this because of the nature of this type of modelling. To arrive at a more efficient and accurate decision, it is necessary to consider the uncertainty in the degradation modelling process. This requires the use of concepts from probability theory. The use of these methodologies requires sufficient track geometry data. Thus, it leads the process to the development of a complex empirical-mechanistic model, which allows a more dynamic and current interaction.

However, it is also necessary to count on the results provided by the numerical approach. Otherwise, the number of simplifications can lead to the study of a totally different scenario or even an error. With this aspect, the finite element method (FEM) can be a useful tool. This is also interesting for railway designers and permanent way managers. Just imagine the amount of money that would need to be applied in experimental testing, or the hassle of spot testing, causing track breaks and eventually affecting users. An initial investment for the numerical model calibration may be sufficient to characterize the entire infrastructure and have a better understanding of predictable problems [28].

There are some specific questions regarding the use of FEM in modelling railway sections related to the large differences between the mechanical properties and size of the elements, and the continuity or otherwise of the layer to be analysed. However, a FEM becomes useful for determining the overall structure behaviour in terms of deflection, making the interaction between elements and layers easy to treat, and understanding and enabling the application of different boundary conditions as well as introducing different geometries within the same model [29].

In turn, in order to deal with the questions regarding specifically with the size of the elements, a discrete element models (DEM) can be applied in complementing the FEM. DEM are numerical procedures, as well, to solve problems that exhibit gross discontinuous behaviour. These methods are able to analyse multiple interacting bodies undergoing large dynamic movements. By modelling the individual particles and computing their motion, the overall behaviour of the granular assembly, which may include unrecoverable deformations, dilation, post-peak behaviour, and anisotropy, is modelled implicitly. Granular material interactions or rock masses can be modelled accurately and realistically since any discontinuous detail can be included in the analysis [30]. Figure 5 illustrates the FEM applied in modelling the railway track deformation, and shows an application to DEM in studying the force transfers in track ballast.

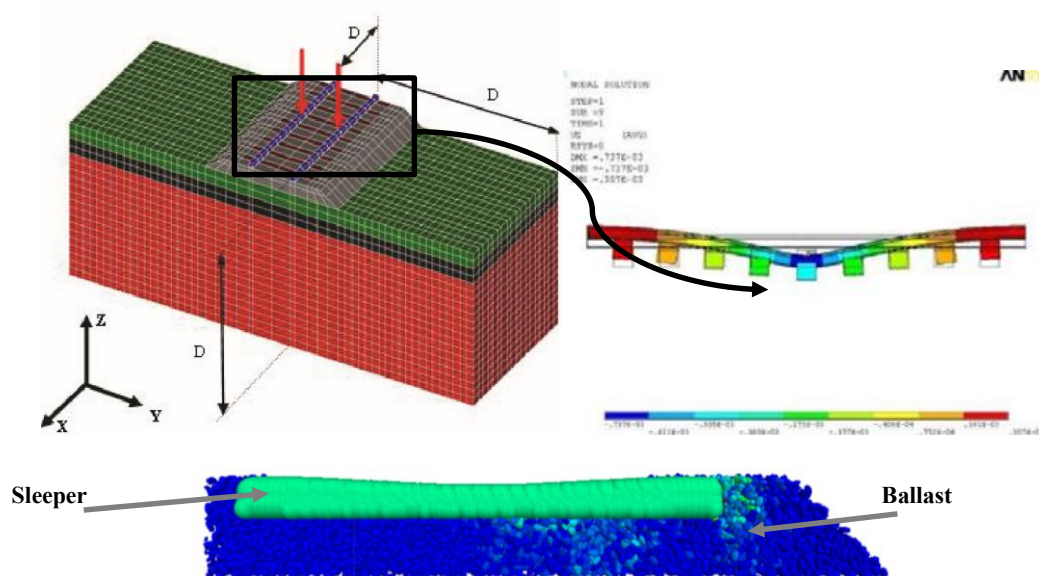


Figure 5. 3D FEM example (left), 3D FEM deformation of the rail-plate-sleeper assembly versus the undeformed configuration (right) [29], and contours of velocity magnitude on DEM track section with ballast depth (bottom) [31]

The numerical results provide a good confidence for evaluating the track deterioration mode, at least when they are applied to complex mechanistic models. However, given the necessity for a more accuracy evaluation, it is necessary obtain the same – or at least approximately – results obtained by experimental approach, determined within a hybrid formulation framework, where some components are modelled numerically while the important calibrations are measured experimentally. This experimental approach can be in field and/or laboratory. For this purpose, since a direct comparison with analytical results is possible, it is important to consider, in the track deterioration process, the results involving the experimental devices selected and set up, registering the simulation or the actual railway track response and its components to the forces and stresses from the traffic, vehicles, and environment (e.g. local temperature variation). Figure 6 illustrates examples of laboratory and field experiments.



Figure 6. Examples of laboratory (left) [32] and field tests [33]

For the data acquisition to be used in the modelling and simulations, it is necessary to identify the applicable tests and their measurement form. Experimental modal analysis (EMA) or modal test is a non-destructive test strategy based on the structure responses to vibration. The vast growth of modal analyses results in more precision and accurate vibration measurements. Additionally, the integration of the analytical models and the experimental results has directed to the sensitive analysis of the structure behaviour [34]. This strategy can be applied in laboratory and field tests. These experiments often use the Hammer impact technique [35] and can be used without damage or obstruction to traffic [34]. Other non-destructive test strategies, most commonly applied in railways, are the track graphing through the track inspection vehicle to evaluate geometry conditions (see figure 7). Ngamkhanong et al. [36] also present a review regarding sensors used for condition monitoring in field.

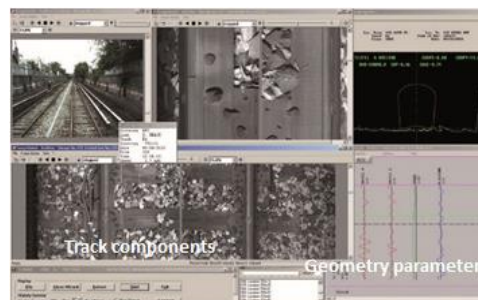


Figure 7. Off-board computer screen showing synchronised video and track data (geometry parameters) by recording car [37]

Based on the advantages and drawbacks presented regarding each model and approach in modelling, its strengths and weakness, as well, and focus on filling the previous gaps discussed, it is proposed, in this paper, a conceptual design to predict the track deterioration process in a railway in-service. Figure 8 presents the Conceptual Design diagram.

The whole track system is designed and maintained to provide satisfactory geometry. That is why there are the track components. Renewal decisions are often governed by the geometry. Roughly speaking, renewal is necessary when too many rail failure repairs spoil the geometry, but ballast is also renewed when it can no longer maintain good geometry. Sleepers and fastenings are considered to have fail when the track gauge cannot be maintained. However, according to Esveld [13], the process of determining whether, when, where, and how best to intervene is far more complex. On the other hand, it is known that as much more complex is the modelling, much more time and resources are necessary to process it. Therefore, it is fundamental to develop a trade-off between time and final result.

The proposed Conceptual Design gives especial attention in modelling the track degradation with the current theoretical options of both models and approaches (figures 2 and 8). In turn, it focus on an empirical-mechanistic model and a hybrid numerical and experimental approach. The adoption of the first one is to map and identify better the interaction between the track components and how each one

influences the other under a wheel loads and environmental effects. In this same model, preventing the uncertainties to imperfect modelling and errors in determination of the input parameters such as axle loads, material strengths, and temperature variation, is recommended to adopt the probability theory such as the Gamma process.

With the second one – the hybrid approach, it is intended to enrich the track deterioration modelling with numerical (finite and discrete elements) and experimental (tests in laboratory and field) analysis. The first one has the objective to improve the interactions among track components, traffic, and environmental, what could be limited by the huge necessity of a complex mathematical procedure. The second (experimental) has the intention to extract measured data from a real situation in situ such as the displacements and forces acting on the track under loads.

Additionally, it is proposed, into the Conceptual Design in order to fit an equilibrium throughout the modelling, one complementary model called ‘model calibrations’. It is the process of adjustment, forcing within the uncertainty margins to obtain a model representation of the track deterioration process that satisfies pre-agreed criteria.

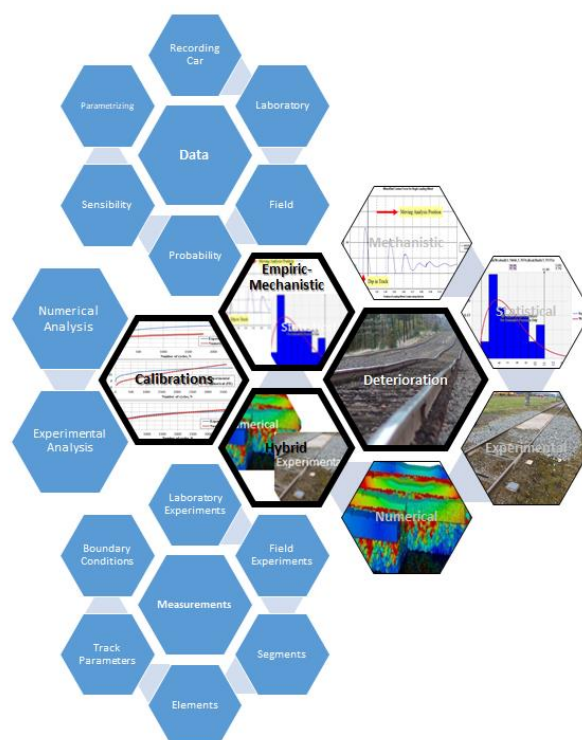


Figure 8. Diagram representing the conceptual design in modelling the track deterioration

4. Conclusions

Determining whether, when, where, and how the track condition (structure and geometry) will fail is far more complex. However, despite of the challenge, it is possible to develop a unique empirical-mechanistic and probabilistic model to deal with complex problems involving permanent way condition, non-analytical equation solutions, or interactions between elements. Differently from other methods, it considers the effects of the deterioration due to the interactions between the track components, track geometry itself, and track geometry and components themselves. This approach is essential to a better understanding of the existing component technology and performance. With the technological advancement of computational methods it is possible to simulate the components behaviour to be analysed, generating an environment closer to reality.

Therefore, the Conceptual Design to improve a hybrid novel for track deterioration, supported on empirical-mechanistic and probability theories, and joined all track geometry and components and their interactions may provide an updated tool to fill the current gaps in modelling the process. It should be, when implemented, an affordable tool for railway engineering and regulatory professionals, perfect for analysis and design in general.

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